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Effect of climate change on halophytic grasslands loss and its impact in the viability of *Gopherus flavomarginatus*

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Abstract

The decrease of the habitat is one of the main factors that affect the survival of *G. flavomarginatus*. This study assesses the halophytic grasslands loss over a period of 30 years in the distribution area of the Bolson tortoise and the effects of climate change on the habitat suitability of these grasslands and its possible impact on this tortoise. Grassland loss was assessed by an analysis of symmetric differences and the habitat suitability model was carried out by the method of overlapping layers raster. Our results showed a grassland loss of 63.7%; however, our current habitat suitability model points out that much of the grassland loss has occurred where the environmental conditions are suitable. These results suggest that anthropic activity is a main factor in the habitat disturbance in the study area. Likewise, the models for years 2050 and 2070 under the criteria RCP 2.6, RCP 4.5, RCP 6.0, suggest that anthropic activity will continue be the main cause of the grassland loss. Therefore, considering the association between the Bolson tortoise and grassland halophyte *Hilaria mutica*, which comprises around 60% of its diet, the viability of the Bolson tortoise depends largely on strategies aimed at protecting the soil that allow the presence of this grassland.

Keywords

Gopherus flavomarginatus; spatial distribution; climate change; halophytic grasslands

Introduction

Climate influences plant and animal distributions due to their requirements related to temperature and humidity (Parmesan and Yohe 2003; Root et al. 2005; Walther et al. 2005; Lavergne et al. 2006). It has been documented that when climatic factors are extreme, these can exceed the level of tolerance of species, preventing the optimal expression of their life cycles (Gutiérrez and Trejo 2014). Each species has a tolerance interval to diverse environmental factors (Walther et al. 2002; Hardy 2003; Dawson and Spannagle 2009); therefore, its distribution depends on their fundamental niche and their biological interactions (Pearman et al. 2008).

Climate change and change of land use are two of the factors that most affect natural systems (Burroughs 2001; Shafer et al. 2001; Iverson et al. 2008; Harsch et al. 2009; IPCC 2014). The effect of the climate change is more severe on arid and semiarid ecosystems than on humid and semihumid ecosystems (Grime et al. 2008). Thereon, it has been mentioned that facing loss of vegetation of the arid zone, the presence and animal behavior that feed on desert plants could be modified, generating a decrease in the distribution area and in size of their populations (Gandiwa and Zisadza 2010). The effects of the transformation of the vegetation, however, are not uniform for all animal species (Fahrig 2003). Species' response to environmental change will be determined by their physiology (climatic tolerance), morphology (i.e., body size), ecology (feeding habits, habitat selection; nesting sites), dispersal capacity and behavioral characteristics (foraging time, general activity). Therefore, there are species with negative responses by decreasing its abundance and/or its distribution, as well local extinction (Midgley et al. 2007), and other species with positive responses reflected in increasing their abundance and expanding their distribution (Stotz et al. 1996; Thomas et al. 2004; Moritz et al. 2008; Lara et al. 2012).

To assess the effect of the climate change on species distribution, ecological niche modeling has been used employing different environmental variables and mathematical algorithms that try to simulate the climate niche of a species and represent it geographically on a map (Parmesan 2006; Mckenney et al. 2007). In most of the studies, on large spatial scales, only climatic variables have been used for predicting spatial distribution of the species (Araújo and Peterson 2012; Anadón et al. 2015). In some cases, dealing with local spatial scales, soil and orography variables have been included (Guisan and Hofer 2003; Pearson et al. 2004; Anadón et al. 2007; Marini et al. 2010; Kreakie et al. 2012), for example, the dependence of herbivores specialized on some plants (Kissling et al. 2007). Nevertheless, it is very difficult to determine spatial data of biological interactions; and for this reason the studies where the interactions are used to assess the distribution area of the species are very scarce (Pearson and Dawson 2003).

Chihuahuan Desert grasslands provide important resources as habitats and food for sustaining a very rich animal diversity (Vickery et al. 1999). However, the degradation of grasslands is one of the main causes of biodiversity loss on a global scale

Figure 1. *Gopherus flavomarginatus* and halophytic grassland *Hilaria mutica*.

(Gavilán 2008). Given this situation, endemic or native species are the most vulnerable (Contreras-Balderas et al. 2003). *Gopherus flavomarginatus* is an endemic tortoise species of the Bolson of Mapimí zone of the Chihuahuan Desert in the north-central México (Figure 1). The Bolson tortoise is considered vulnerable by IUCN Red List (2017). This species inhabits halophytic grasslands of *Hilaria mutica* on which it feeds, presenting an apparently mandatory association (Aguirre et al. 1979). Therefore, there exists a close interaction between the presence of the grassland and that of the tortoise.

Historically, the Bolson tortoise was distributed from the southwestern USA to the center of México. However, it is currently confined to the area known as the Bolson of Mapimí (Lemos-Espinal and Smith 2007). Considering the low dispersal capacity of the Bolson tortoise and its dependence on the halophytic grass *H. mutica*, a reduction of this grassland, brought about by climate change in the Bolson of Mapimí, would be expected having a strong impact on the viability of the tortoise. Therefore, the goals of this study are: (i) to estimate the change in halophytic grasslands from 1980-2013 period on the current distribution range of *G. flavomarginatus*, (ii) to estimate the projected effect of climate change for the years 2050 and 2070 on the distribution of halophytic grasslands in the Chihuahuan Desert, and (iii) to assess the possible impact of the halophytic grasslands changes on the viability of *G. flavomarginatus*.

Materials and methods

Study area

The Chihuahuan Desert has an approximate area of 507,000 km² and elevations from 800 to 2500 m-asl; it extends from central México northward to southern Texas, Arizona, and New México. The mean annual precipitation varies from 175 to 400 mm. The characteristic vegetation is microphyllous desert scrub, rosette desert scrub, crassicaule desert scrub, and grasslands, among others (Rzedowski 1978). About 80% of the soils are derived from calcareous materials (Sutton 2000). Halophytic grasslands of *H. mutica* are distributed throughout the Chihuahuan Desert, whereas the tortoise occurs only in the central zone, in the region known as Bolson of Mapimí, where the Mapimí Biosphere Reserve is located (Lemos-Espinal and Smith 2007).

Zonification of the distribution area of the Bolson tortoise

Sixty one records of *G. flavomarginatus* were identified, with these points we delimited a Minimum Convex Polygon (MCP) of 15,895.5 km² that represents the distributional area of the Bolson tortoise. This polygon was zoned according to the densities of the geographic points using the clustering K-means method (Software CrimeStat V. 3.2, 2009).

Influence of the environmental factors on distribution of halophytic grassland

In order to identify loss and gain areas of halophilic grasslands (1980–2013) we used a symmetric difference analysis (Software ArcMap V. 10.1; ESRI 2012). The analysis was performed by using a quadrant of 32,300 km² (MCP2) product of add a buffer zone of 10 km around the perimeter of MCP. To this quadrant was added information of land use and vegetation distribution (INEGI 1991, 2013). Likewise, we provided current environmental data (19 climatic layers) with a spatial resolution of 2.5 minutes (~5 km²), obtained from Worldclim (Hijmans et al. 2005); The bioclimatic variables of Worldclim reflect aspects of temperature and precipitation and have been used successfully for niche models (Davis et al. 2008; Jezkova et al. 2009).

Subsequently, within the area MCP2 were settled 232 quadrants out of 100 km², each one. In each quadrant we added the corresponding value for each bioclimatic variable, as well as the information of presence and absence of the halophytic grasslands. In order to identify the bioclimatic variables that explain the presence and absence of the halophytic grasslands in the study area, was used an analysis of discriminant factors (canonical) under the generalized linear model. This analysis was performed using the library "MASS" (Venables and Ripley 2002) in the software R (version 3.1.3).

Habitat suitability models

For modeling the habitat suitability of halophytic grasslands under current climatic conditions in the Chihuahuan Desert, we used the retained bioclimatic variables in the discriminant analysis. The selected variables were annual mean temperature, mean diurnal range, minimum temperature of the coldest month, annual precipitation, and precipitation of wettest quarter, as well as substrate texture data (INEGI 2004). Based on these variables we performed an analysis of frequencies with the purpose of obtaining the climatic profile (maximum and minimum) of the halophytic grasslands. Later, the habitat suitability was modeled using an Additive Overlay Analysis of layer raster method (ArcMap V. 10.1), which delimits the potential habitat suitability of one species based on knowledge of its climatic profile. To these are given a weighting according to the importance of the layer and abundance of the points on the polygon, and the cells are extracted from the raster layer by a logical search. Outlet layers contain only the values of the cells or pixels extracted from the input layer and output layers that were used in the superposition processes.

The same climatic profile was used for modeling habitat suitability for the scenario of the climatic change to 2050 and 2070 in the Chihuahuan Desert. We used data as scenarios of the climatic change corresponding to the extrapolated with Beijing Climate Center Climate System Model (BCC-CSM1-1, this was chosen at random from a group of 19 climate models) for the years 2050 and 2070 under different Representative Concentration Pathways (RCP): RCP 2.6 = +2.6 W/m², RCP 4.5 = +4.5 W/m², RCP 6.0 = +6.0 W/m², and RCP 8.5 = +8.5 W/m² were used as scenarios of the climatic change. Under the scenario RCP 2.6 a minor intensity of the effects of the climate changes is expected, while with the scenario RCP 8.5 the intensity will be greater (Weyant et al. 2009). The model additive overlay of layer raster predict habitat suitability as a function of environmental variables and species occurrence data, this habitat suitability is represented by a scale ranging from 0 (low suitability) to one (high fitness), we used a cut-off point of 0.5.

The emergence of new technologies and recent assumptions about socioeconomic development, as well as observations of environmental factors such as land use and land cover change have been considered in this new generation of scenarios (Moss et al. 2010; Rogelj et al. 2012; van Vuuren 2012). The RCPs explicitly explore the impact of different climate policies in addition to the no-climate-policy SRES scenarios (van Vuuren et al. 2011b) and provide an important reference point to investigate the potential implications of climate change on ecosystems (van Vuuren et al. 2011a).

For the validation of the model were used the zones with presence of halophytic grasslands in the Chihuahuan Desert reported by the Comisión Nacional para el Conocimiento y Uso de la Biodiversidad (CONABIO) (2015).

Exchange rate

To assess the climate change impact on the habitat suitability of the halophytic grasslands we obtained the percentage change for each scenario using the following formula (Gutiérrez and Trejo 2014):

% of change = $[(S1 - S0)/S0]*100$,

Where:
$S0$, is the total surface of the study area, according to the base scenario.
$S1$, is the total surface occupied in the study area under change conditions.

Results

Three zones in the distribution area of *G. flavomarginatus* were identified, these zones were classified as "A" with 2,649.99 km², "B" with 5,472.21 km², and "C" with 2,657.11 km² (Figure 2). The zone "A" coincides with the polygon of the Reserve of Mapimí Biosphere, and it is the lesser extension of the three identified zones (Figure 2). For MCP2 (quadrant of 32,300 km²), in a period of 30 yrs, we recorded a halophytic grasslands loss of 1,286.66 km² and a gain of 518 km² (Figure 2); therefore, for the year 2013 the extension of the halophytic grasslands in the MCP2 was 1350.44 Km². The transformed Wilks value, obtained from discriminant analysis shows that the null hypothesis should be rejected ($\lambda = 0.834$, $x^2 = 56.478$, g.l. = 18, p = 0.000); therefore, the two discriminant groups (presence and absence) should be considered as distinct.

The current model habitat suitability identifies the greatest part of the localities where halophytic grasslands had been reported in the Chihuahuan Desert (CONABIO 2015) (Table 1, Figure 3); the projected habitat suitability for Chihuahuan Desert shows that habitat suitability loss was relatively low for the scenarios RCP 6.0, RCP 4.5, and RCP 6.0 for the years 2050 and 2070 (Table 2, Figure 3). However, under the scenario RCP 8.5 for the years 2050 and 2070 the models of habitat suitability show a loss of 43.18% and 89.3%, respectively. Considering the scenario RCP 8.5 for year 2050, halophytic grasslands only it remains in B zone; while for year 2070 disappear completely the habitat suitability in the current distribution area of the Bolson tortoise (Table 2, Figure 3). Under the scenario RCP 8.5 for 2050 and 2070, the loss of habitat suitability for halophytic grassland was much higher than for the rest of the scenarios (Table 2). In RCP 2.6 we obtained the lower estimates of reductions of habitat suitability for grasslands.

Discussion

The results of this study show that halophytic grassland loss in the current distribution area of *G. flavomarginatus* has been a continuous process, in as much as in a period of
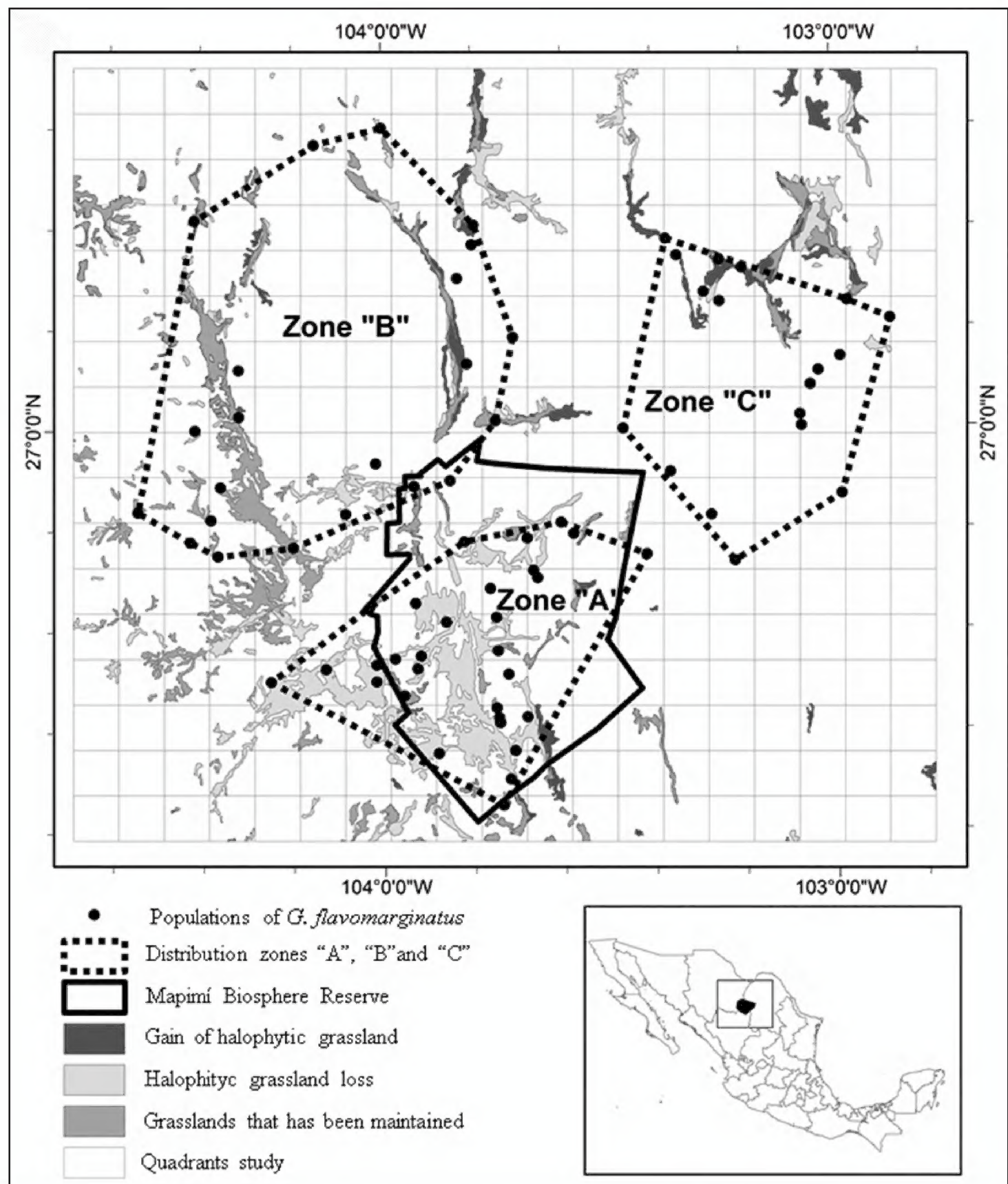
Figure 2. Distribution of gain and loss of the halophytic grassland in an area of 32,300 km². Black spots show populations of *G. flavomarginatus*; dotted lines show distribution zones "**A**", "**B**" and "**C**" of the species; the black line indicates the Mapimí Biosphere Reserve; dark grey color shows the zones with gain of halophytic grassland; light grey color shows the zones of halophytic grassland loss; medium grey color shows areas with grasslands that has been maintained; the grid make reference to squares of 100 km² in the study area.

30 years its reduction has been 63.7%, with the zone "A" being the most affected. In this context, halophytic grasslands loss for the Chihuahuan Desert has been attributed to the climatic change and to the anthropic factors (e.g., agriculture and cattle; Vavra et al. 1994; Archer et al. 1995; Hodgson and Illius 1996; Aguirre et al. 1997; Moleele
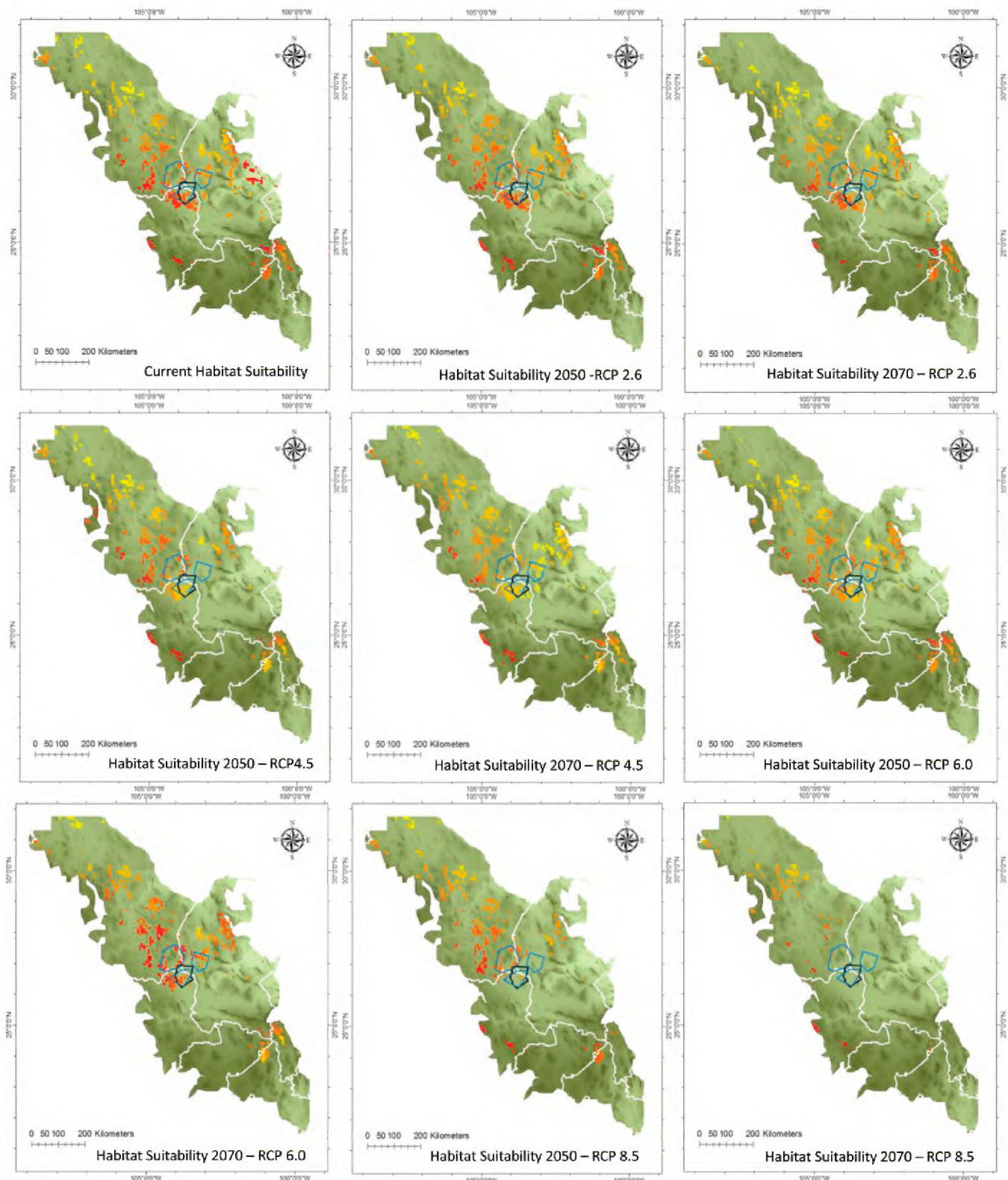
Figure 3. Habitat suitability models of the halophytic grasslands projected for Chihuahuan Desert. White lines show states boundaries; black lines refer to the Mapimí Biosphere Reserve; blue lines indicate distribution zones of *G. flavomarginatus*.

and Perkins 1998; Van Auken 2000). In this regard, Archer (1994) pointed out that the grassland loss is an event that is happening in arid and semiarid ecosystems worldwide; while Comstock and Ehleringer (1992) and Cook and Irwin (1992) showed that the climate is the main factor to explain the variation in vegetation patterns.

The current habitat suitability model of this study indicates that climatic conditions of the area that showed the highest loss of halophytic grassland inside the known distribution range of *G. flavomarginatus* (zone "A") are appropriate for the presence of this grassland. Data on land use and vegetation presented by Instituto Nacional de

Table 1. Habitat suitability for distribution of *G. flavomarginatus* considering the different climatic scenarios assessed.

Habitat suitability	Zone A	Zone B	Zone C
Current habitat suitability	1,087.99 km²	999.49 km²	594.04 km²
Habitat suitability RCP 2.6-2050	1,087.56 km²	999.48 km²	594.02 km²
Habitat suitability RCP 4.5-2050	1,007.85 km²	1,027.28 km²	0 km²
Habitat suitability RCP 6.0-2050	1,179.83 km²	1,065.37 km²	624.11 km²
Habitat suitability RCP 8.5-2050	143.066 km²	1,023.241 km²	0 km²
Habitat suitability RCP 2.6-2070	1,087.43 km²	999,46 km²	593.92 km²
Habitat suitability RCP 4.5-2070	1,008.61 km²	1,117.54 km²	657.39 km²
Habitat suitability RCP 6.0-2070	921.69 km²	999.77 km²	510.25 km²
Habitat suitability RCP 8.5-2070	0 km²	25.7 km²	0 km²

Table 2. Change rate of the habitat suitability area for halophytic grassland in Chihuahuan Desert considering current and future climatic conditions (2050 and 2070) under concentrations of greenhouse gases RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5.

Current model	Model 2050	Model 2070	Model 2050	Model 2070	Model 2050	Model 2070	Model 2050	Model 2070
	RCP 2.6		RCP 4.5		RCP 6.0		RCP 8.5	
29,715.73	27,413.14	26,133.87	23,414.74	26,644.12	26,401.96	22,390.37	16,288.26	5,546.78
Change rate (%)	-7.74	-12.05	-21.20	-10.33	-11.15	-24.65	-45.18	-81.33

Estadística y Geografía (INEGI 2013) show that zone "A" and its surroundings presents a strong agricultural and cattle impact. Likewise, it has been noted that reduction and fragmentation of the vegetation cover in the Natural Protected Area of Mapimí Biosphere placed inside Zone "A" is caused by overgrazing (CONANP 2006). In this manner, based on this information, it is possible to point out that beyond the influence of the environmental factors in determining the presence or absence of halophytic grassland, anthropic activities are the main factors that are influencing the loss of this grassland in the current distribution area of the Bolson tortoise by causing fragmentation of this corridor route of halophytic grassland among zones A, B, and C.

In this context, it has been documented that changes in vegetal species distribution promote that animal species also modify their behavior and distribution (Gurd et al. 2001; Steffan-Dewenter et al. 2002). However, when individuals of one species are not able to disperse and colonize new areas with suitable habitat quality or do not possess a wide range of physiological tolerance, their extinction is highly likely (Holt 1990; Kattan and Murcia 2003; Brooks et al. 2004; Uezu et al. 2005; Wilcox and Thurow 2006). In this regard, it has been pointed out that this situation is frequently observed in specialist species (Gascon et al. 1999). For example, it has been documented that grassland fragmentation in the Chihuahuan Desert has affected the biological biodiversity causing isolation and reduction in 60% of the bird populations that inhabit grasslands (Desmond et al. 2005). Likewise, in *Cynomys mexicanus*, an endangered

mammal and strongly associated with halophytic grassland in the Chihuahuan Desert, it has been seen that the distance among colonies of this species increase with the grassland fragmentation preventing natural dispersal and the interactions of the animals among populations (Yeaton and Flores-Flores 2006).

For the lizard species *Uma exul* and *Uma paraphygas*, it has been reported that their specificity on dune ecosystems and their low dispersal capacity reduce the probability of migration to places where the habitat conditions are suitable to live. These two species show very low genetic variability; therefore, it has been pointed out that these species are in critical condition because of the transformation of their habitat (Gadsden et al. 1993; Gadsden 1997; Ballesteros-Barrera et al. 2007). Likewise, since 1987, in 20 of 50 amphibian species of cloud forest from Monte Verde, Costa Rica, including the endemic Golden Frog (*Incilius periglenes*), as well as species of the *Anolis* genus have disappeared because of habitat fragmentation (Schneider 1999).

Accordingly, considering the association between Bolson tortoise and the halophytic grass *H. mutica* that comprises 60% of its diet (Aguirre et al. 1979), and taking into account the decreased food availability in the environment, the Bolson tortoise tends to reduce its home range (Hoogland 2006). Therefore, its low dispersal ability (Ureña-Aranda et al. 2015), low genetic variability (Ureña-Aranda and Espinosa de los Monteros 2012), and fragmentation and loss of grassland *H. mutica* are the main threats for the Bolson tortoise, because these factors favor isolation of the populations of this tortoise by intensifying the low genetic variability of the species. These conditions promote less resistance to extreme temperatures, drought events, change in food availability, emerging diseases, among other features, thus causing population extinction (Hoelzel et al. 2002; Russello et al. 2004; Zhang et al. 2004).

On the other hand, expectations of climate change for years 2050 and 2070 under scenarios RCP 2.6, RCP 4.5, and RCP 6.0 show a slight decrease in habitat availability for halophytic grassland in the Chihuahuan Desert, zones A and B, however show relative stability. This suggests that fragmentation of halophytic grassland in the range of the Bolson tortoise will depend on the change in land use. Under conditions of a pessimistic scenario (RCP 8.5) change rate of the habitat suitability area for halophytic grassland in the Chihuahuan Desert for years 2050 and 2070 will be of -45.186 and -81.333%, respectively. Under this scenario the viability of the Bolson tortoise is heavily compromised.

In conclusion, viability of the Bolson tortoise will depend on the strategies of protection and the land conservation allowing for the presence of halophytic grassland composed of *H. mutica*. In this regard, conservation programs for the Bolson tortoise and its habitat currently are addressed mainly within the Mapimí Biosphere Reserve; however, according to the available evidence, this zone is strongly affected by anthropogenic factors. Likewise, monitoring programs of the populations and habitat conditions of the Bolson tortoise are performed in an area of 1 km^2 scattered inside the Protected Natural Area (CONANP 2016). Faced with this situation, conservation programs of the habitat are needed for allowing connection of the populations inside and outside the Protected Natural Area. Therefore, we propose protection of the A, B, and C zones and the connections among them, so that in this way genetic interchange

among populations can be favored. On the other hand, due to threats of climate change, it is necessary to develop an *ex situ* conservation program for *G. flavomarginatus* as well as the conservation of the area that show a habitat suitability outside the current distribution range of the Bolson tortoise, thinking about reintroduction of the species. Also, it is necessary to point out that the algorithms of potential area of habitat suitability involve a certain level of uncertainty that becomes worse in the projections to simulated scenarios (Pearson et al. 2006). However, we consider that our results provide an early warning about the possible consequences of the current activities on land use and the climate change due to increasing temperature.

Author contributions

Acknowledgments

References

Araújo MB, Peterson AT (2012) Uses and misuses of bioclimatic envelope modeling. Ecology 93: 1527–1539. http://dx.doi.org/10.1890/11-1930.1

Aguirre G, Morafka DJ, Adest GA (1997) Conservation strategies for the Bolson Tortoise, *Gopherus flavomarginatus*, in the Chihuahuan Desert. In: Van Abbema J (Ed.) Proceedings: Conservation, Restoration, and Management of Tortoises and Turtles-An International Conference. Conference. New York Turtle and Tortoise Society, New York, 333–338.

Anadón JD, Graciá E, Giménez A, Fahd S, Fritz U (2015) Individualistic responses to climate changes: niche differentiation promotes diverging Quaternary range dynamics in the subspecies of *Testudo graeca*. Ecography 38: 956–966. https://doi.org/10.1111/ecog.01163

Anadón JD, Giménez A, Martínez M, Palazón JA, Esteve MA (2007) Assessing changes in habitat quality due to land use changes in the spur-thighed tortoise *Testudo graeca* using hierarchical predictive habitat models. Diversity and Distributions 13: 324–331. https://doi.org/10.1111/j.1472-4642.2007.00343.x

Aguirre G, Adest GA, Recht M, Morafka DJ (1979) Preliminary investigations of the movements, thermoregulation, population structure and diet of the Bolson tortoise (*Gopherus*

flavomarginatus) in the Mapimí Biosphere Reserve, Durango, México. Proceedings Desert Tortoise Council 149–165.

Archer S, Schimel DS, Holland EA (1995) Mechanisms of shrubland expansion: land use, climate, or CO2? Climatic Change 29: 91–99. http://dx.doi.org/10.1007/BF01091640

Archer S (1994) Woody Plant Encroachment into Southwestern Grasslands and Savannas: Rates, Patterns and Proximate Causes. In: Vavra M, Laycock W, Pieper R (Eds) Ecological Implications of livestock herbivory in the West. S.R.M. Denver, CO, 13–68.

Ballesteros-Barrera C, Martínez-Meyer E, Gadsden H (2007) Effects of land-cover transformation and climate change on the distribution of two microendemic lizards, genus *Uma*, of Northern México. Journal of Herpetology 41: 733–740. https://doi.org/10.1670/06-276.1

Brooks ML, D'Antonio CM, Richardson DM, Grace JB, Keeley JE, DiTomaso JM, Hobbs RJ, Pellant M, Pyke D (2004) Effects of invasive alien plants on fire regimes. BioScience 54: 677–688. https://doi.org/10.1641/0006-3568(2004)054[0677:EOIAPO]2.0.CO;2

Burroughs WJ (2001) Climate change a multidisciplinary approach. Cambridge University Press, London: 248. https://doi.org/10.1017/S0016756803338129

Comstock JP, Ehleringer JR (1992) Plant adaptation in the Great basin and Colorado Plateau. Great Basin National 52: 195–215. http://scholarsarchive.byu.edu/ gbn/vol52/iss3/1

Contreras-Balderas S, Almada Villela P, Lozano Vilano M, García Ramírez M (2003) Freshwater fish at risk or extinct in Mexico. Reviews in Fish Biology and Fisheries 12: 241–251. https://doi.org/10.1023/A:1025053001155

Cook JG, Irwin LL (1992) Climate–vegetation relationships between the Great Plains and Great Basin. The American Midland Naturalist 127: 316–326. https://doi.org/10.2307/2426538

CONABIO (2015) Comisión Nacional Para el Conocimiento y Uso de la Biodiversidad. http://www.biodiversidad.gob.mx/ecosistemas/images/mapa3_3.jpg

CONANP (2006) Comisión Nacional de Áreas Naturales Protegidas – Programa de conservación y manejo Reserva de la Biosfera Mapimí, México. http://www.conanp.gob.mx / datos_abiertos/DGCD/76.pdf

CONANP (2016) Comisión Nacional de Áreas Naturales Protegidas – Monitoreo de la tortuga del Bolsón (*Gopherus flavomarginatus*) en la Reserva de Biosfera Mapimí. http://www.conanp.gob.mx/programas/pdf/Anexo%202%20Protocolo%206%20RB%20Mapimi.pdf

Davis ED, Koo MS, Conroy C, Patton JL, Moritz C (2008) The California Hotspots Project: identifying regions of rapid diversification of mammals. Molecular Ecology 17: 120–138. https://doi.org/10.1111/j.1365-294X.2007.03469.x

Dawson B, Spannagle M (2009) The complete guide to climate change. Routledge, New York, 394 pp. https://www.amazon.com/Complete-Guide-Climate-Change/dp/0415477905

Desmond MJ, et al. (2005) Habitat associations and conservation of grassland birds in the Chihuahuan Desert Region: two case studies in Chihuahua, México. In: Cartron JL E, Ceballos G, Felger RS (Eds) Biodiversity, ecosystems, and conservation in northern México. Oxford University Press, New York, 439–51.

ESRI (2012) Environmental Scientific Research Institute – ArcGIS 10.1. Redlands, California.

Fahrig L (2003) Effects of habitat fragmentation on biodiversity. Annual Review of Ecology, Evolution, and Systematics 34: 487–515. https://doi.org/10.1146/annurev.ecolsys.34.011802.132419

Gadsden HE (1997) Autoecología de las lagartijas de arena *Uma paraphygas* y *Uma exsul* (Sauria: Phrynosomatidae) en las dunas del Bolsón de Mapimí. Informe final del Proyecto L173.

Gadsden HE, Méndez de la Cruz FR, Gil-Martínez R, Casas-Andreu G (1993) Patrón reproductor de una lagartija (*Uma paraphygas*) en peligro de extinción. Boletín de la Sociedad Herpetológica Mexicana, 5: 42–50. http://sociedad herpetológi camexicana.org.mx/publicaciones/boletin-de-la-shm/1993-vol-5/

Gandiwa E, Zisadza P (2010) Wildlife management in Gonarezhou National Park, southeast Zimbabwe: Climate change and implications for management. Nature and Faune 25: 95–104. http://www.fao.org/docrep/013/am071e/am071e00.pdf

Gascon C, Lovejoy TE, Bierregaard RO Jr, Malcolm JR, Stouffer PC, Vasconcelos HL, Laurance W, Zimmerman B, Tocher M, Borges S (1999) Matrix habitat and species persistence in tropical forest remnants. Biological Conservation 91: 223–229. https://doi.org/10.1016/S0006-3207(99)00080-4

Gavilán RG (2008) La vegetación de alta montaña. In: Redondo M, Palacios M, López F, Santamaría T, Sánchez D (Eds) Avances en biogeografía Universidad Complutense de Madrid, Facultad de Geografía e Historia, Madrid, 165–174.

Guisan A, Hofer U (2003) Predicting reptile distributions at the mesoscale: relation to climate and topography. Journal of Biogeography 30: 1233–1243. https://doi.org/10.1046/j.1365-2699.2003.00914.x

Gurd DB, Nudds TD, Rivard DH (2001) Conservation of mammals in eastern North American wildlife reserves: how small is too small? Conservation Biology 15: 1355–1363. https://doi.org/10.1111/j.1523-1739.2001.00188.x

Gutiérrez I, Trejo E (2014) Efecto del cambio climático en la distribución potencial de cinco especies arbóreas de bosque templado en México. Revista Mexicana de Biodiversidad 85: 179–188. https://doi.org/10.7550/rmb.37737

Grime JP, Fridley JD, Askew AP, Thompson K, Hodgson JG, Bennett R (2008) Long-term resistance to simulated climate change in an infertile grassland. Proceedings of the National Academy of Sciences, USA, 105: 10028–10032. https://doi.org/10.1073/pnas.0711567105

Hardy JT (2003) Climate Change: Causes, Effects and Solutions. John Wiley and Sons, West Sussex, England. http://www.wiley.com/WileyCDA/WileyTitle/productCd-0470850191.html

Harsch MA, Hulme PE, McGlone MS, Duncan RP (2009) Are treelines advancing? A global meta-analysis of treeline response to climate warming. Ecology Letters 12: 1040–1049. https://doi.org/10.1111/j.1461-0248.2009.01355.x

Hijmans RJ, Cameron SE, Parra JL, Jones PG, Jarvis A (2005) Very high resolution interpolated climate surfaces for global land areas. International Journal of Climatology 25: 1965-1978. https://doi.org/10.1002/joc.1276

Hoelzel AR, Fleischer RC, Campagna C, Le Boeuf BJ, Alvord G (2002) Impact of a population bottleneck on symmetry and genetic diversity in the northern elephant seal. Journal of Evolutionary Biology 15: 567–575. https://doi.org/10.1046/j.1420-9101.2002.00419.x

Hodgson J, Illius AW (1996) The ecology and management of grazing systems. CAB International. Wallingford, United Kingdom: 466.

Hoogland LJ (2006) Conservation of the Blacktailed Praired Dog. Saving North America's Western Grasslands. Island Press: 350.https://islandpress.org/book/conservation-of-the-black-tailed-prairie-dog

Holt RD (1990) The microevolutionary consequences of climate change. Trends in Ecology and Evolution 5: 311–315. http://dx.doi.org/10.1016/0169-5347(90)90088-U

INEGI (1991) Instituto Nacional de Estadística y Geografía – Conjunto de datos vectoriales de la carta de uso del suelo y vegetación: escala 1: 250 000. Serie I (continuo nacional). Instituto Nacional de Estadística, Geografía e Informática. http://www.inegi.org.mx/

INEGI (2004) Instituto Nacional de Estadística y Geografía – Conjunto de datos vectorial edafológico: escala 1:250000. Serie II (continuo nacional). Instituto Nacional de Estadística, Geografía e Informática. http://www.inegi.org.mx/

INEGI (2013) Instituto Nacional de Estadística y Geografía – Conjunto de datos vectoriales de la carta de uso del suelo y vegetación: escala 1: 250 000. Serie V (continuo nacional). Instituto Nacional de Estadística, Geografía e Informática. http://www.inegi.org.mx/

IPCC (2014) Intergovernmental Panel on Climate Change – Climate Change 2013: The physical science basis: Working group I contribution to the fifth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

IUCN (2017) International Union for Conservation of Nature – IUCN Red List of Threatened Species. http://www.iucnredlist.org/details/9402/0

Iverson LR, Prasad AM, Matthews SN, Peters M (2008) Estimating potential habitat for 134 eastern US tree species under six climate scenarios. Forest Ecology and Management 254: 390–406. https://doi.org/10.1016/j.foreco.2007.07.023

Jezkova T, Jaeger JR, Marshall ZL, Riddle BR (2009) Pleistocene impacts on the phylogeography of the Desert Pocket Mouse (*Chaetodipus penicillatus*). Journal of Mammal 90: 306–320. https://doi.org/10.1644/08-MAMM-A-243.1

Kattan GH, Murcia C (2003) A review and synthesis of conceptual frameworks for the study of forest fragmentation. In: Bradshaw GA, Mooney HA (Eds) How landscapes change: human disturbance and ecosystem fragmentation in the Americas. Springer-Verlag, New York, 183–200. https://doi.org/10.1007/978-3-662-05238-9_11

Kissling WD, Rahbek C, Böhning-Gaese K (2007) Food plant diversity as broad-scale determinant of avian frugivore richness. Proceedings of the Royal Society B 274: 799-808. https://doi.org/10.1098/rspb.2006.0311

Kreakie BJ, Fan Y, Keitt TH (2012) Enhanced migratory waterfowl distribution modeling by inclusion of depth to water table data. PLoS ONE 7(1). https://doi.org/10.1371/journal.pone.0030142

Lara C, Feria-Arroyo TP, Dale J, Muñoz J, Arizmendi MC, Ornelas JF (2012) Potential effects of the climate change in the distribution of hummingbirds: a study case with hummingbirds from the genus *Amazilia* and *Cynanthus*. Ornitologia Neotropical 23: 57–70.

Lavergne S, Molina J, Debussche M (2006) Fingerprints of environmental change on the rare Mediterranean flora: a 115-year study. Global Change Biology 12: 1466–1478. https://doi.org/10.1111/j.1365-2486.2006.01183.x

Lemos-Espinal J, Smith H (2007) Anfibios y reptiles del estado de Chihuahua, México. UNAM-CONABIO, México, 550 pp.

Levine N (2009) CrimeStat: a spatial statistics program for the analysis of crime incident locations, version 3.2. Ned Levine and Associates, Houston, TX, and the National Institute of Justice, Washington, DC.

Marini MÂ, Barbet-Massin M, Lopes LE, Jiguet F (2010) Predicting the occurrence of rare Brazilian birds with species distribution models. Journal of Ornithology 151: 857–866. https://doi.org/10.1007/s10336-010-0523-y

McKenney DW, Pedlar JH, Lawrence KM, Campbell KL, Hutchinson MF (2007) Potential impacts of climate change on the distribution of North American trees. BioScience 57: 939–948. https://doi.org/10.1641/B571106

Midgley GF, Thuiller W, Higgins SI (2007) Plant species migration as a key uncertainty in predicting future impacts of climate change on ecosystems: progress and challenges. In: Canadell JG, Pataki DE, Pitelka LF (Eds) Terrestrial Ecosystems in a Changing World. Springer, New York, 129–137. https://doi.org/10.1007/978-3-540-32730-1_11

Moleele NM, Perkins JS (1998) Encroaching woody plant species and boreholes: is cattle density the main driving factor in the Olifants Drift communal grazing lands, south-eastern Botswana? Journal of Arid Environments 40: 245–253. https://doi.org/10.1006/jare.1998.0451

Moritz C, Patton JL, Conroy CJ, Parra JL, White GC, Beissinger SR (2008) Impact of a century of climate change on small-mammal communities in Yosemite National Park, USA. Science 322: 261–264. https://doi.org/10.1126/science.1163428

Moss R, et al. (2010). The next generation of scenarios for climate change research and assessment. Nature 463: 747–756. https://doi.org/10.1038/nature08823

Pearson PN, et al. (2004) Paleogene and Cretaceous sediment cores from the Kilwa and Lindi areas of coastal Tanzania: Tanzania Drilling Project Sites 1–5. J. Journal of African Earth Sciences 39: 25–62. https://doi.org/10.1016/j.jafrearsci.2004.05.001

Pearson RG, et al. (2006) Model-based uncertainty in species range prediction. Journal of Biogeography 33: 1704–1711. https://doi.org/10.1111/j.1365-2699.2006.01460.x

Pearson RG, Dawson TP (2003) Predicting the impacts of climate change on the distribution of species: are bioclimate envelope models useful? Global Ecology and Biogeography 12: 361–371. https://doi.org/10.1046/j.1466-822X.2003.00042.x

Parmesan C (2006) Ecological and evolutionary response to recent climatic change. Annual Review of Ecology, Evolution, and Systematics 37: 637–669. https://doi.org/10.1146/annurev.ecolsys.37.091305.110100

Pearman PB, Guisan A, Broennimann O, Randin CF (2008) Niche dynamics in space and time. Trends in Ecology and Evolution 23: 149–158. https://doi.org/10.1016/j.tree.2007.11.005

Parmesan C, Yohe G (2003) A globally coherent fingerprint of climate change impacts across natural systems. Nature 421: 37–42. https://doi.org/10.1038/nature01286

R Core Team (2015) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. http://www.R-project.org/

Rzedowski J (1978) Vegetación de México. Limusa, México.

Rogelj J, Meinshausen M, Knutti R (2012) Global warming under old and new scenarios using IPCC climate sensitivity range estimates. Nature Climate Change 2: 248–253. https://doi.org/10.1038/nclimate1385

Root TL, MacMynowski DP, Mastrandrea MD, Schneider SH (2005) Human-modified temperatures induce species changes: joint attribution. Proceedings of the National Academy of Sciences, USA 102: 7465–7469. https://doi.org/10.1073/pnas.0502286102

Russello MA, Gladyshev E, Miquelle D, Caccone A (2004) Potential genetic consequences of a recent bottleneck in the Amur tiger of the Russian far east. Conservation Genetics 5: 707–713. https://doi.org/10.1007/s10592-004-1860-2

Shafer SL, Bartlein PJ, Thompson RS (2001) Potential changes in the distribution of western North America tree and shrub taxa under future climate scenarios. Ecosystems 4: 200–215. https://doi.org/10.1007/s10021-001-0004-5

Schneider SH (1999) Amphibian declines in the cloud forest of Costa Rica: responses to climate change? USGCRP Seminar, 29 September 1999.

Stotz DF, Fitzpatrick JW, Parker III TA, Moskovits DK (1996) Neotropical birds: ecology and conservation. The University of Chicago Press, Chicago. EE.UU.

Steffan-Dewenter I, Munzenberg U, Burger C, Thies C, Tscharntke T (2002) Scale-dependent effects of landscape structure on three pollinator guilds. Ecology 83: 1421–1432. https://doi.org/10.1890/0012-9658(2002)083[1421:SDEOLC]2.0.CO;2

Sutton A (2000) El Desierto Chihuahuense, nuestro desierto. Fondo Mundial para la Naturaleza. http://www.pronatura.org

Thomas CD, et al. (2004) Extinction risk from climate change. Nature 427: 145–148. https://doi.org/10.1038/nature02121

Uezu A, Metzger JP, Vielliard JM (2005) The effects of structural and functional connectivity and patch size on the abundance of seven Atlantic Forest bird species. Biological Conservation 123: 507–519. https://doi.org/10.1016/j.biocon.2005.01.001

Ureña-Aranda CA, Espinosa de los Monteros A (2012) The genetic crisis of the Mexican Bolson tortoise (*Gopherus flavomarginatus*: Testudinidae). Amphibia-Reptilia 33: 45–53. https://doi.org/10.1163/156853811X621508

Ureña-Aranda, CA, Rojas-Soto O, Martínez-Meyer E, Yáñez-Arenas C, Landgrave Ramírez R, Espinosa de los Monteros A (2015) Using Range-Wide Abundance Modeling to Identify Key Conservation Areas for the Micro-Endemic Bolson tortoise (*Gopherus flavomarginatus*). PLoS ONE 10(6): e0131452. https://doi.org/10.1371/journal.pone.0131452

van Vuuren DP (2012) A proposal for a new scenario framework to support research and assessment in different climate research communities. Global Environmental Change 22: 21–35. http://www.sciencedirect.com/science/journal/09593780

van Vuuren DP, Edmonds JA, Kainuma M, Riahi K, Weyant J (2011a) A special issue on the RCPs. Climatic Change 109: 1–4. https://doi.org/10.1007/s10584-011-0157-y

van Vuuren DP, et al. (2011b) The representative concentration pathways: an overview. Climatic Change 109: 5–31. https://doi.org/10.1007/s10584-011-0148-z

Van Auken OW (2000) Shrub invasions of North American semiarid grasslands. Annual Review of Ecology and Systematics 31: 197–215. https://doi.org/10.1146/annurev.ecolsys.31.1.197

Vavra M, Laycock W, Pieper R (1994) Ecological implications of livestock herbivory in the West. Society for Range Management, Denver, Colorado. https://www.cabdirect.org/cabdirect/abstract/19940706040

Venables WN, Ripley BD (2002) modern Applied Statistics with S. Fourth Edition. Springer, New York.

Vickery P, Tubaro PP, Silva J, Peterjohn B, Herkert J, Cavalcanti R (1999) Conservation of grassland birds in the Western Hemisphere. Studies in Avian Biology 19: 2–26. https://miami.pure.elsevier.com/en/publications/conservation-of-grassland-birds-in-the-western-hemisphere

Walther GR, Berger S, Sykes MT (2005) An ecological "footprint" of climate change. Proceedings of the Royal Society of London (Series B) 272: 1427–1432. https://doi.org/10.1098/rspb.2005.3119

Walther G, et al. (2002). Ecological responses to recent climate change. Nature 416: 389–395. https://doi.org/10.1038/416389a

Weyant J, et al. (2009) Report of 2.6 versus 2.9 Watts/m^2 RCPP evaluation panel. Integrated Assessment Modeling Consortium. https://www.ipcc.ch/meetings /session30/inf6.pdf

Wilcox BP, Thurow TL (2006) Emerging issues in rangeland ecohydrology: vegetation change and the water cycle. Rangeland Ecology and Management 59: 220–224. http://dx.doi.org/10.2111/05-090R1.1

Yeaton RI, Flores-Flores JL (2006) Patterns of occurrence and abundance in colony complexes of the mexican prairie dog (*Cynomys mexicanus*) in productive and unproductive grasslands. Acta Zoologica Mexicana 22: 107–130. http://www.redalyc.org/pdf/402/40223164008.pdf

Zhang B, Fang SG, Xi YM (2004) Low genetic diversity in the Endangered crested ibis (*Nipponia nippon*) and implications for conservation. Bird Conservation International 14: 183–190. https://doi.org/10.1017/S0959270904000231